Proceedings of the ASME 2022
International Design Engineering Technical Conferences
and Computers and Information in Engineering Conference
IDETC/CIE2022
August 14-17, 2022, St. Louis, MO, USA

DETC2022-90673

STEP-NC COMPLIANT DATA REPRESENTATIONS FOR POWDER BED FUSION IN ADDITIVE MANUFACTURING

Fahad Ali Milaat[1 *], Paul Witherell[1], Martin Hardwick[2], Ho Yeung[1], Vincenzo Ferrero[1], Laetitia Monnier[1,3], Matthew Brown[4]

[1]Engineering Laboratory, National Institute of Standards and Technology,
100 Bureau Drive, Gaithersburg, MD 20899, USA
[2]STEP Tools Inc.
14 First Street, Troy, NY 12180, USA
[3]Laboratoire Informatique de Bourgogne, Universite de Bourgogne Franche-Comte,
9 Avenue Alain Savary, 21000 Dijon, France
[4]School of Engineering and Applied Sciences, University of the District of Columbia,
4200 Connecticut Avenue, N.W. Washington, DC 20008, USA

ABSTRACT

Powder bed fusion (PBF) is an additive manufacturing (AM) technology that uses powerful beams to fuse powder material into layers of scanned patterns, thus producing parts with great geometric complexity. For PBF, process parameters, environmental control, and machining functions play critical roles in maintaining fabrication consistency and reducing potential part defects such as pores and grain growth. However, such defects can be attributed to poor data representations in the form of tessellated geometry and incoherent process plans. To address this issue, the Standard for the Exchange of Product model data Numerical Control (STEP-NC) recently added standardized data elements, entities, and attributes specifically for AM applications. Yet, the current STEP-NC data representations for AM lack definitions of process parameters and scan strategies that are commonly used in PBF processes. Therefore, characterization of the relationship between joint features, especially for PBF in AM, is missing. To bridge this gap, in this paper, an amended STEP-NC compliant data representation for PBF in AM is proposed. Specifically, the characteristics of the interlayer relationships in PBF, along with beam technology and AM strategy controls, are defined. Simulation results demonstrate the feasibility of granular process planning control, and the potential for producing high-quality parts with exact geometry and tolerance.

Keywords: Data exchange, data/information modeling, intelligent manufacturing, process planning.

1. INTRODUCTION

Additive Manufacturing (AM) is a rapidly evolving domain that is poised to become the future of the industry [1]. In AM, parts are built from the ground up using additive, layer-by-layer, fabrication processes, contrasting traditional fabrication processes that subtract material from the top down using a variety of cutting tools. Since the first major patent of "stereolithography" in 1986 by Charles Hull [2], AM has transitioned from rapid prototyping into full commercial production thanks to the advancements made in three-dimensional (3D) printing machines [3][4]. AM encompasses different types of 3D printing technologies, where each technology has its own challenges and characteristics [5]. Powder bed fusion (PBF) is a type of AM process where thermal energy selectively fuses regions of a powder bed [6]. PBF can be subdivided into two branches, laser-based powder bed fusion (L-PBF) and electron beam melting (EBM). This work focuses on the L-PBF technology that uses a high-power laser to selectively melt geometric patterns into layers of metal powder, forming a near fully dense freeform part [7]. When manufacturing with L-PBF, the resulting part quality is established by many process parameters, such as laser power, scan speed, hatch space, and layer thickness [8][9]. However, L-PBF is susceptible to the manifestation of process flaws such as cracks, residual stresses, and pores [10][11]. Therefore, calibrating the process parameters is an important step towards regulating thermal distribution,

* Contact author: fahad.milaat@nist.gov

optimizing microstructure formation, and assuring the stability of the manufactured part.

It is well known that digital thread applications for design, manufacturing, inspection, and maintenance favor the utilization of computer-aided 3D modeling and associated data exchange formats [12] [13]. However, not all data exchange formats satisfy the requirements for PBF processes. For example, popular data exchange formats, such as STereoLithography (STL) [14] and Additive Manufacturing File (AMF) [15], describe the surface of a 3D part in the form of a triangulated mesh. However, these formats only approximate the geometry, and their files become quite large as the geometric complexity of the solid part increases. In addition, geometry approximated data formats lack definitions for process parameters that are needed to drive the fabrication of an additive part. In contrast, the Standard for the Exchange of Product model data compliant Numerical Control (STEP-NC) [16][17] is well suited for advance AM processes, providing accurate Geometric Dimensioning and Tolerancing (GD&T), and enabling process planning of AM workpieces, features, and operations.

STEP-NC has first been introduced to answer the smart manufacturing needs of standardization for modern computer numerical control (CNC) machines. STEP-NC allows design data to be encapsulated into the machine process to: 1) reduce the loss of information between the design and the manufacturing stages, 2) reflect the geometry properties of the part into the machining process, and 3) replace the obsolete G-code [18] machining instructions. Thus, using STEP-NC to bypass G-code would be a real improvement toward facilitating the AM digital threads [19]. The ISO 14649-17 [20] standard has been introduced to represent AM processes and adapt them to STEP-NC. However, the current version of the ISO 14649-17 standard lacks definitions for process parameters that control the process of fusing the scan paths of a layer, and fusing the additive layers together. To bridge this gap, this paper proposes STEP-NC compliant data representations for PBF manufacturing in AM. More specifically, the proposed representations enable control of PBF procedures by defining operation, technology, and scan strategy parameters for process planning. Such process parameters are essential for PBF manufacturing, which enable the optimization of the part's quality and prevent the occurrence of fabrication flaws and defects.

The structure of this paper is detailed as follows. Section 2 covers the literature review. Section 3 describes the standardized AM data representation and identifies current challenges. Section 4 presents the proposed AM data representation. Section 5 discusses the data mapping and modeling of the proposed data representation. Section 6 concludes this paper.

2. LITERATURE REVIEW

STEP-NC has gained tremendous attention in the open literature in recent years. The ubiquity of AM technology, and the demand for precise product data representations, enabled the adoption of STEP-NC throughout the AM product lifecycle. Such adoptions could range from specific AM processes such as 3D slicing, to complete AM digital chains. A selection of recent research efforts that utilized STEP-NC data models for AM applications are discussed next.

For AM application processes, Um et al. [21] proposed a STEP-NC-based representation method for process planning and remanufacturing in AM applications. The proposed method used geometric reasoning to find discrepancies between the original part's STEP-NC file and the defective scanned part to be repaired. The STEP-NC file is then updated with the repair feature and the workingstep of the executed operation, a milling process to remove the defective surface and flatten the part, and a laser cladding process to create the repair feature. Finally, the authors conducted a comparative case study between STL and STEP-NC data formats, respectively, showed that STL data accumulated errors after several geometric processes, whereas solid model representations in STEP-NC data kept the errors low and enabled high accuracy process planning and tolerance inspection. In the application of 3D slicing, Um et al. [22] proposed a squashing algorithm to process complex sliced layers without missing volumes. To increase the accuracy in the geometry definition process, the authors presented a data representation based on STEP-NC for multi-material and multi-directional layers in a boundary-representation standard model. The data representation followed the AM standard of ISO 14649-17 [20]. Results from case studies showed that using boundary representation and the squashing algorithm in the geometric process of AM improved the inaccuracies caused by legacy data representation.

Regarding a digital thread architecture, Bonnard et al. [23] proposed a STEP-NC data model for AM technologies and presented a STEP-NC platform on an industrial AM system for data model implementation and validation. The methodology adopted by the authors for introducing AM in the CNC-based ISO 14649-1 [24] data model consisted of one ISO 14649-10 [20] general process data for all manufacturing processes. In addition, the method created specific parts as process data for AM in ISO 14649-17 [20] and tools for AM in ISO 14649-171. According to the authors, this method enabled machining processes and AM processes to be on the same level, whereas the general process data allowed for a unique data model for multi-process manufacturing, and alternative process plans for the same part geometry with different processes or with different combinations of processes. To validate the STEP-NC AM data model, the authors conducted experimental tests of fabricating two test parts, which have been constructed and validated using the proposed digital thread platform.

To demonstrate the flexibility of STEP-NC data models, Rodriguez et al. [19] presented a method that applied STEP-NC programming in AM processes based on the machining STEP-NC data model of the ISO 10303 application protocol 238 [16]. The proposed methodology consisted of five implementation activities, which handled the slicing of the 3D CAD model, generating the AM STEP-NC program, building the AM machine kinematic model, simulating toolpath, and fabricating the part. For experimental validation, a test part was fabricated using a RepRap 3D printer, where a G-code program was generated through the post-processor of a STEP-NC machine.

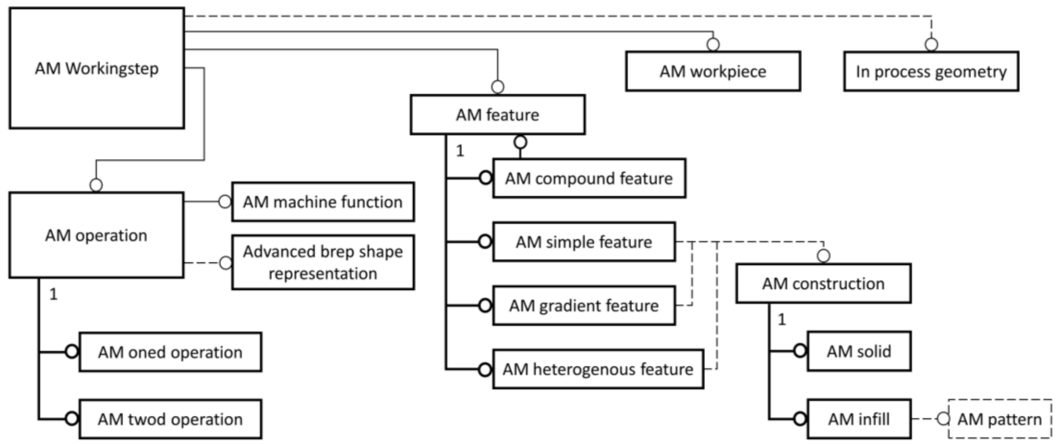

FIGURE 1: A DIAGRAM REPRESENTATION OF THE ISO 14649-17 STANDARD ENTITIES APPLICABLE FOR POWDER BED FUSION IN ADDITIVE MANUFACTURING.

Finally, the toolpath information contained in the G-code format file was interpreted by the controller to generate movements on the powered axes of the RepRap printer.

For qualification and inspection, Riaño et al. [25] proposed a STEP-NC-based integrated architecture for closed-loop inspection in AM digital thread. The proposed architecture consisted of an AM linear parallel delta robot, an inspection system using a coordinate measuring machine (CMM), and a quality control system. For this architecture, the authors used a STEP-NC digital model as the fundamental basis of integration, which contained the solid model and metadata of the design specifications such as GD&T. In a case study, the authors performed closed-loop inspection through execution of inspection planning, measurement collection, feature inspection, tolerance operation, and correlation of the system results.

3. STANDARDIZED AM DATA REPRESENTATIONS

This section presents the AM standardization of STEP-NC data representations in two parts. The first part reviews some of the standardized STEP-NC data representations for AM in the ISO 14649-17 [20] standard that are applicable to PBF processes. The second part identifies several challenges when applying the current standard definitions to PBF processes.

3.1 STEP-NC for AM

The ISO 14649-17 standard, here forth named part-17, is a key form of data representation for AM definitions in STEP-NC. Figure 1 shows a diagram of the data entities that are represented in part-17. This standard, along with other STEP-NC standards [16][17], enable AM data exchange between computer-aided design (CAD), computer-aided process planning (CAPP), and computer-aided manufacturing (CAM) systems. Essentially, a CAD software enables an engineer to design, or model a part with great complexity and full GD&T. In STEP-NC part-17, the volumetric part model is described as an AM workpiece. Multiple AM workpiece(s) can be concatenated to form a manufacturing hierarchical structure. To fabricate a part, engineers use a CAPP software to generate the program necessary for executing the process plans. The Executable element of the STEP-NC ISO 10303-238 [17] standard commands the execution of processes either sequentially or in parallel. The information associated with the atomic transformation of an executed process is included in the AM workingstep entity. The AM workingstep holds descriptions of an AM feature, which is the geometry under fabrication, and an AM operation, which is the required process parameters of the fabrication.

The geometry of an AM feature can be compounded by linking multiple features, such that each feature can be defined as an AM simple feature, AM gradient feature, or AM heterogenous feature. As the name suggests, the AM simple feature defines a simple additive geometry with a skin and a core, such that the skin thickness is assumed to be uniform, and the selected color and material are fixed. On the other hand, the AM gradient feature enables the definition of graded colors and materials inside an AM feature. The AM heterogeneous feature uses a freeform formula to describe atomic mixtures of multiple materials and colors within the same feature. The AM construction entity specifies how an AM feature of a part is constructed either as a solid, or as an infill based on the density and direction of a predefined pattern such as honeycomb, concentric, rectilinear, etc.

The AM operation entity describes the process parameters attributed to the manufacturing of an additive feature, which are AM OneD operation and AM TwoD operation. In addition, AM operation identifies the machine functions and the support structure needed for this operation. Nevertheless, the process parameters of an AM operation depend on the type of the AM fabrication process. For example, the AM OneD operation is applicable for additive deposition processes, where a freeform operation repeats the deposition of one filament of material at a time until the full geometry is obtained. On the other hand, the AM TwoD operation is designed particularly for layer-by-layer AM parts. Here, the two-dimensional (2D) operation specifies the elementary surface geometry of each layer and defines the thickness of a layer based on the normal direction.

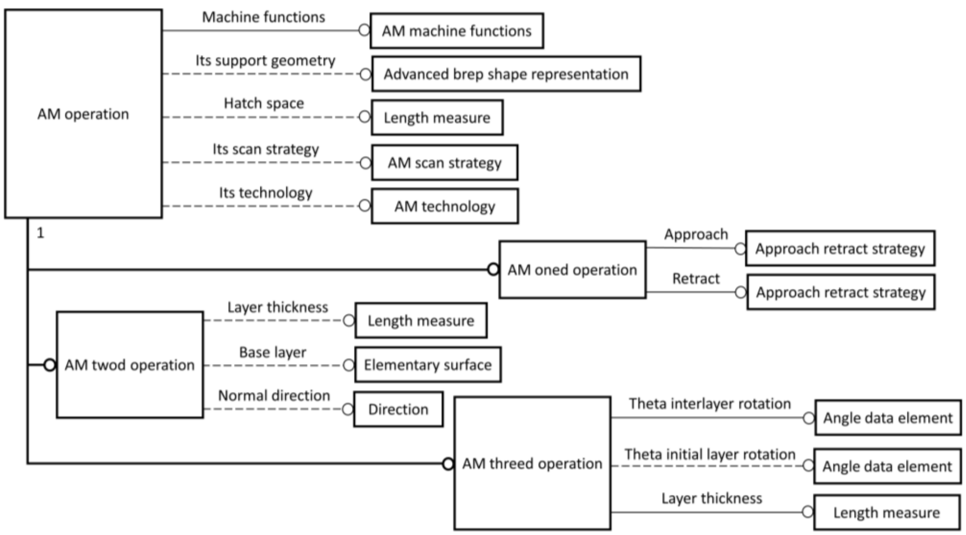

FIGURE 2: A DIAGRAM REPRESENTATION OF THE AMENDED AM OPERATION ENTITY, AND THE PROPOSED AM THREED OPERATION ENTITY.

3.2 Identified Challenges

The AM data representations that have been included in the STEP-NC Part 17 standard do not fully capture the necessary requirements for process control in precision AM applications such as PBF. The following discussions identify several challenges, and possible ways to overcome them.

One of the main characteristics of AM feature is the ability to specify the way a feature is constructed by using the AM construction entity. This is achieved by specifying the direction, the density, and the type of the chosen pattern. However, the specifications associated with the scan patterns are not currently defined. For instance, common scan strategies in PBF might contain geometric patches within a pattern, also called islands, which require boundary specifications and a rotation angle for each patch [26] [27]. Without specifications, AM process plans might suffer from compatibility issues that arise during part fabrication. Thus, there should be a modular definition of scan strategies that reflects the essential characteristics of a pattern and provides the parameters necessary to maintain control of the powder fusion process.

The attributes of the AM TwoD operation entity identify the geometry, the thickness, and the direction for additively building a feature layer-by-layer. However, the AM TwoD operation entity lacks process parameters for describing the 3D build. It is well known that the laser power, scan speed, hatch space, layer thickness, and scan strategy influence the geometry and density of the resulting part fabricated using laser based PBF (L-PBF) [26]. Therefore, careful application and control of these process parameters are necessary to ensure the quality of the additive part and reduce the internal defects that might occur during fabrication. Furthermore, process parameters of PBF require frequent adjustments to their settings to meet the demands of the in-situ additive processes. Therefore, the settings of these parameters should enable adaptive control and systematic response to the steps of the fabrication process.

4. PROPOSED AM DATA REPRESENTATIONS

This section details the proposed STEP-NC compliant data representations for PBF processes in AM. Specifically, the defined data are contained in four STEP-NC compatible entities. These entities are the AM operation, the AM ThreeD operation, the PBF technology, and the AM scan strategy. In what follows, a detailed discussion of the design and function of each entity is presented.

Figure 2 illustrates the amended AM operation entity and its subtype entities including the proposed AM ThreeD operation. The combined entities provide the processing parameters and scanning strategies necessary for additively building a geometric AM feature of a part using PBF. The AM operation entity includes two standardized attributes, machine functions and its support geometry, respectively, and three new attributes: 1) hatch space, 2) its scan strategy, and 3) its technology. Figure 3 shows the hatch space that represents the distance between two consecutive laser scan paths. The measurement of the hatch

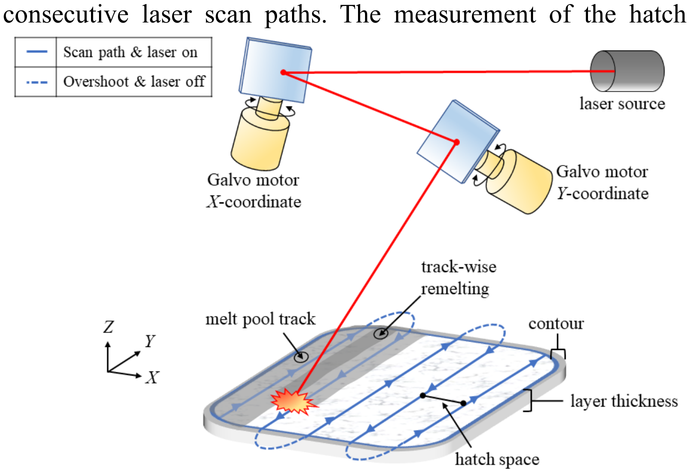

FIGURE 3: AN ILLUSTRATION OF THE OPTICAL SCAN CONTROLLER, PROCESS PARAMETERS, AND AM STRIPE STRATEGY FOR LASER-BASED POWDER BED FUSION.

space is specified using the millimeter (mm) unit and the length measure variable, which takes in a real number value. It is important to note that selecting a proper hatch space depends on the settings of other process parameters such as the laser scan speed and the laser spot diameter among others [27]. This is to ensure the consistency of the melt pool track and to achieve adequate track-wise, and layer-wise remelting [28]. Its scan strategy is the attribute associated with the AM scan strategy entity, which contains parameters of scan patterns that are common in PBF processes. Likewise, its technology is the attribute connected to the powder bed fusion technology entity, which holds the parameters that drive the in-situ powder fusion processes. The detailed data representations of the AM scan strategy and the powder bed fusion technology entities are discussed later in this section. The proposed AM ThreeD operation entity defines three attributes: 1) theta interlayer rotation, 2) theta initial layer rotation, and 3) layer thickness. Figure 4 illustrates the theta interlayer rotation, which represents the measured angle of rotation in degrees between the scan strategy of the current layer and the previous layer.

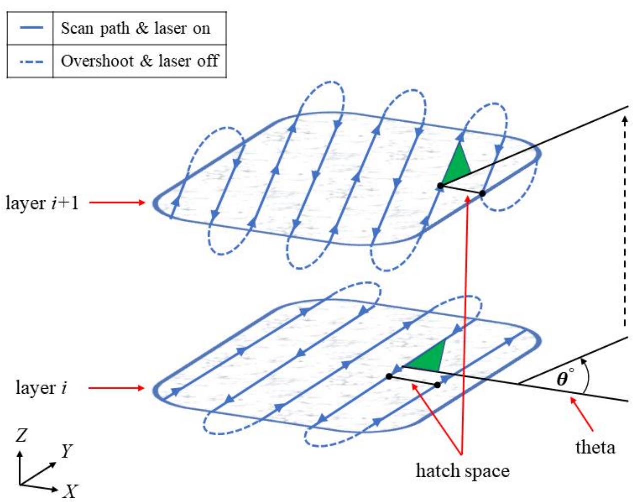

FIGURE 4: AN ILLUSTRATION OF THETA INTERLAYER ROTATION OF A STRIPE STRATEGY BETWEEN THE LAYERS i AND i+1 WITH THE SAME HATCH SPACE.

Similarly, the theta initial layer rotation is the measured angle of rotation in degrees of the first scanned layer of an AM feature. In PBF, the scan strategies of successive layers are rotated slightly, e.g., 45°, 67°or 90°, to regulate thermal distribution over the powder surface and control in-situ grain size and growth direction of the powder material [26] [29]. The layer thickness is the predefined thickness of a layer, which could be directly inherited from the AM TwoD operation, or specified according to the geometry of the AM feature. When selecting the thickness of a layer, the powder material properties such as thermal conductivity and density need also to be considered. This is critical for a successful build because the laser melted area of the powder, also called melt pool, need to be large enough to connect the molten tracks in each layer and deep enough to connect to the previous layer [26].

The AM scan strategy is a supertype entity that contains the definitions of two subtype entities, the AM stripe strategy, and the AM chess strategy. Figure 5 shows the diagram of the proposed AM scan strategy entity. The AM stripe strategy partitions the scan area into segments of stripes as shown in Figure 3. The objective of this scan strategy is to control the thermal gradients for each scanned track by specifying the width of the stripe [30]. The stripe width is defined as a real number with a mm unit and is contained in the length measure variable. The AM chess strategy, also called island strategy, is a common scan pattern in PBF manufacturing where the slice of a feature is segmented into rectangular patches akin to a chess board. The length and width of each rectangle are defined as real numbers with mm units using the length measure variable. In addition, the orientation of each rectangular island can be rotated independently using the theta inter-island rotation attribute. In PBF, interlayer rotation plays an important role in balancing the temperature distribution and reducing residual stress [29][31].

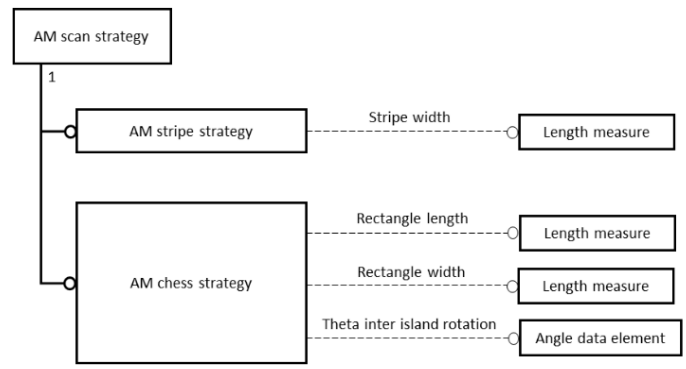

FIGURE 5: A DIAGRAM OF THE AM SCAN STRATEGY ENTITY AND ITS SUBTYPE ENTITIES: AM STRIPE STRATEGY AND AM CHESS STRATEGY.

Figure 6 shows a diagram of the powder bed fusion technology entity, which is desgined to be a subtype entity contained in the AM technology entity. The PBF technology entity specifies four attributes: beam diameter, beam power, beam power mode, and scan speed, which are used by an optical scan controller (OSC) system of a L-PBF machine [9].

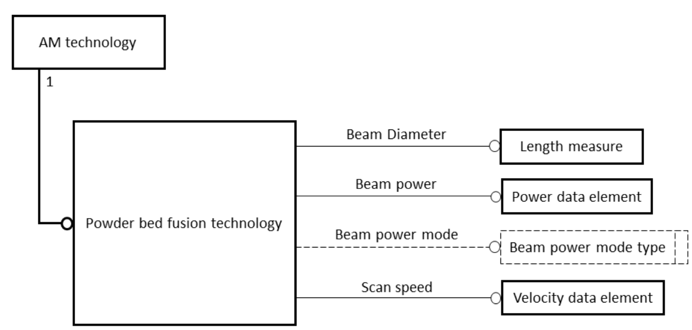

FIGURE 6: A DIAGRAM OF THE POWDER BED FUSION TECHNOLOGY ENTITY.

The main components of the OSC are the laser beam energy source and the galvanometer motors and mirrors that control the XY-coordinates of the laser beam movement, see Figure 3. The

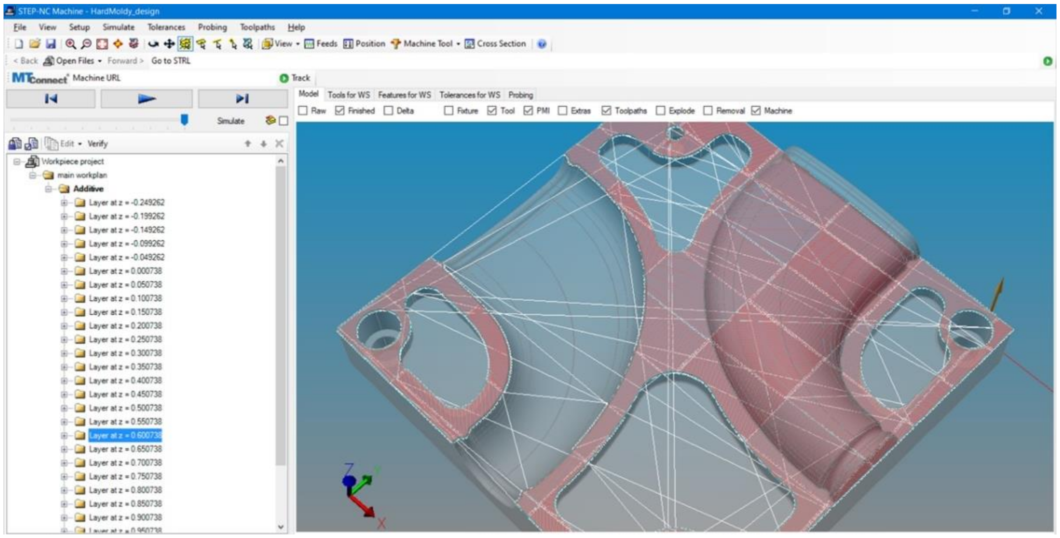

FIGURE 7: A SIMULATION OF AM THREE-D OPERATION DESCRIBING THE LASER SCAN PATH OF A SLICED LAYER USING THE AM CHESS STRATEGY [36].

beam diameter attribute defines the diameter of the laser spot with a mm unit using the length measure variable. The ability to set the diameter of a laser spot could be a factor in increased productivity, such that a larger laser spot would reduce the number of scan lines [32]. The beam power attribute specifies the energy output of the laser unit in Watts and is represented by the power data element variable. The beam power mode attribute selects from three power mode types: constant power, constant power density, and thermal adjusted power. The constant power mode keeps the laser power constant, and the constant power density mode holds the power to speed ratio constant, whereas the thermal adjusted power mode compensates for the local variation of thermal property by changing the laser power [9]. The scan speed attribute represents the rate at which the laser beam moves over the designated scan path. The scan speed is measured in millimeter per second (mm/s) and is assigned a real number value. Regulating the scan speed of a laser plays a key role in combating various microstructure and materials-related issues such as micro-segregation, undesired texture, and columnar grains [8].

5. DISCUSSION

In this section, the steps taken to model the proposed STEP-NC data representations for PBF in AM are detailed. Figure 7 demonstrates the simulation validation of the proposed operation processes. The development of the mapping strategy for the proposed data representations is influenced by the Additive Manufacturing Metrology Testbed (AMMT) of the National Institute of Standards and Technology (NIST) [33]. The AMMT is a fully customized metrology instrument for fabricating metal L-PBF parts, which include various measuring sensors to collect in-situ monitoring data such as encoder, tower camera, and high-speed coaxial camera [9]. For the proposed STEP-NC data representation, the developed strategy involved mapping the process planning and manufacturing parameters of the AMMT to their corresponding entities in the STEP-NC part-17 standard. The development stages of the mapping strategy shall be discussed below.

The first stage is a comprehensive system analysis of the AMMT front-end to understand the utility and behavior of the system. The process planning and command controls of the AMMT are driven by the Simple Additive Manufacturing (SAM) utility, which provides a reference architecture for an open platform AM control software [7][9]. The SAM utility uses a 3D CAD model and user-specified inputs to generate an AM G-code file [9], which is a modified version of the RS-274 standard [34]. The AM G-code file describes the 2D coordinates of the scan path, the laser power, and the laser diameter for each layer. Then, an interpreter module converts the AM G-code file into time-stepped commands, enabling the AMMT controller to operate the power outputs of the laser unit and the XY-coordinates of the Galvanometer motors. The time-stepped commands are based on the XY2-100 protocol [35], where each command line is executed by the AM controller every 10 microseconds (μs) [9]. The comprehensive analysis of the AMMT system provided important information regarding the utilization of data elements and the executions of layer-by-layer building commands.

The second stage is a gaps analysis that identifies crucial process parameters in the AMMT system that were not defined in the current STEP-NC part-17 standardization. When examining the path planning step in the SAM utility, the programming procedure is contingent on user inputs that specify the process parameters of each layer, such as the layer thickness and the rotation angle of the scan path. In addition, the user specifies the type of scan strategy and the hatch space that separates each path. However, the SAM process parameters related to the laser power, the laser power mode, and the scan speed are dependent on prior knowledge of the material properties of the powder metal, and the technological capabilities of the AMMT OSC system. Despite including the layer thickness, elementary surface, and normal direction in the AM TwoD operation entity, the path planning parameters that enable control of the thermal gradients and the microstructure formations must be well defined in PBF manufacturing. Therefore, the proposed data representations encapsulate the necessary path planning parameters in a modified AM operation entity, where the defined process parameters of additive layers are succinctly linked in a uniform, STEP-NC data format.

In the third stage, the proposed AM data representations are tested through simulation. The STEP Tools software [36] is used to simulate the solid 3D geometry, the 3D slicing, and the toolpath plans for each layer of the tested part. Figure 7 shows the relationship between the AM ThreeD, AM TwoD and AM OneD operations. The AM OneD operation describes a "patch" or contour where all the process parameters are constant. The AM TwoD operation describes the array of patches on a layer with each patch oriented and positioned for best manufacturing performance, as highlighted in Figure 7. The AM ThreeD operation describes a list of layers that together make a solid. Each layer has its own orientation and may have its own customized array of patches. In the simple situation a complete solution is generated by defining a single set of parameters as an AM ThreeD operation. Algorithms then generate each layer and each patch. However, in practice, thin walls and tight tolerances require special consideration. Therefore, different parameters are set for the critical layers by defining AM TwoD operations. Similarly, for the regions on the layer where the walls are thin, AM OneD operations are defined to give precise control over the manufacturing.

Following the development of the mapping strategy and the simulation results, several challenges have been realized. In AM, the relationship between process parameters and geometry parameters are not necessarily clear and need to be well understood. For instance, specifying the hatch space value depends on the settings of other parameters, such as the laser beam power and diameter, which are technology parameters, the layer thickness, which is a geometry parameter, and the width of a stripe, which is a scan strategy parameter. Such an observation kept recurring throughout the development of the data mapping effort. One explanation is that the process control in PBF impacts the structure of a part at the micro-scale, meso-scale, and macro-scale [37]. Therefore, the assigned parameters, whether from geometry or process, rely on compounded parametric relationships that are designed to optimize the microstructure formation, and maintain the manufacturing stability of the final part. Another challenge is faced when considering the terminology related to the defined parameter. For example, when reviewing the AM literature, many interchangeable terminologies are observed, such as the terms scan pattern and scan strategy [8][9]. However, it is more challenging to define standardized terminologies that the AM community would agree upon [6]. Likewise, when designing data representations for a STEP-NC compliant entity, many combinations of attributes and datatypes could be formulated to achieve similar definitions or equivalent processes. In addition, the declaration of a parameter might occur at the global level of a supertype entity, such as AM operation, or at the local level of a subtype entity, such as AM ThreeD operation. Proper selection of the declaration scope of a parameter could mean the difference between a globally available definition and a custom-built one. Therefore, defining a parameter or representing a data element should encompass not only the syntax of the definition, but also the semantics that reflect its purpose and function.

6. CONCLUSION AND FUTURE WORK

This paper presented STEP-NC compliant, AM data representations for laser-based, fused powder bed processes. The proposed AM data representations encapsulate process parameters of L-PBF in a hierarchal structure using the AM operation entity. Furthermore, the parameters associated with the PBF technology and the AM scan strategy, respectively, are defined. Simulation results demonstrated the applicability of the proposed data representations for granular control of process parameters in PBF manufacturing.

For future work, an investigation into the modeling, process planning, and fabrication of a real L-PBF part using the proposed STEP-NC data representations will be attempted. The implementation of this approach is critical for examining the compatibility and functionality of the defined parameters in a real-world, AM build scenario. In addition, the findings of this approach are expected to broaden the scope of the analysis in information representation, and the mapping of more parameters and definitions across different segments of the AM data spectrum.

DISCLAIMER

REFERENCES

[1] Ford, Sharon L.N. (2014) "Additive Manufacturing Technology: Potential Implications for U.S. Manufacturing Competitiveness," Economics of Innovation eJournal, September 24, 2014. Available Online: https://www.usitc.gov/journals/Vol_VI_Article4_Additive_Manufacturing_Technology.pdf

[2] Hull C. Apparatus for production of three-dimensional objects by stereolithography. US Patent 4,575,330, March 1986.

[3] Lipson, H. and M. Kurman, *Fabricated: The new world of 3D printing*. 2013: John Wiley & Sons.

[4] Sells, E., et al., RepRap: The Replicating Rapid Prototyper: Maximizing Customizability by Breeding the Means of Production. Handbook of Research in Mass Customization and Personalization, Forthcoming, 2009.

[5] Frazier, William E. “Metal Additive Manufacturing: A Review.” *Journal of Materials Engineering and Performance* 23, no. 6, June 1, 2014. doi: 10.1007/s11665-014-0958-z
[6] ISO/ASTM 52900:2021 Additive manufacturing — General principles — Fundamentals and vocabulary. ISO/TC 261 Additive manufacturing, Nov. 2021.
[7] Yeung, H., Neira, J., Lane, B., Fox, J. and Lopez, F. (2016) “Laser Path Planning and Power Control Strategies for Powder Bed Fusion Systems,” *Proceedings of the Solid Freeform Fabrication Symposium*, Austin, TX, US. Available Online: https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=921536
[8] Oliveira, J.P., LaLonde, A.D., Ma, J. (2020) “Processing parameters in laser powder bed fusion metal additive manufacturing,” *Materials & Design*, vol. 193, August 2020, doi: 10.1016/j.matdes.2020.108762.
[9] Yeung, H., Hutchinson, K., Lin, D. (2021) “Design and implementation of laser powder bed fusion additive manufacturing testbed control software,” *32nd Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference*, Austin, TX, US, Aug. 2-4, 2021, Available Online: https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=933133
[10] Kim, F.H., Moylan, S.P. (2018) “Literature Review of Metal Additive Manufacturing Defects,” NIST Advanced Manufacturing Series (NIST AMS), 2018, pp. 100–116. doi: 10.6028/NIST.AMS.100-16
[11] Kim, F.H., Yeung, H., Garboczi, E.J. (2021) “Characterizing the effects of laser control in laser powder bed fusion on near-surface pore formation via combined analysis of in-situ melt pool monitoring and X-ray computed tomography,” *Additive Manufacturing, vol. 48, part A,* Dec. 2021, doi: 10.1016/j.addma.2021.102372.
[12] Lipman, R. and McFarlane, J. (2015) “Exploring Model-Based Engineering Concepts for Additive Manufacturing,” *Proceedings of the 26th Solid Freeform Fabrication Symposium*, Austin, TX, USA. Available Online: https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=919076
[13] Witherell, P., Jones, A. and Lu, Y. (2016), Additive Manufacturing: A Trans-disciplinary Experience, Trans-Disciplinary Systems Complexity Book, Springer, New York, NY.
[14] Roscoe, L. "Stereolithography interface specification." *America-3D Systems Inc* 27, no. 2020 (1988): 10.
[15] ISO/ASTM 52915:2020 Specification for additive manufacturing file format (AMF) Version 1.2. ISO/TC 261 Additive manufacturing, March 2020.
[16] ISO 14649-10:2004 Industrial automation systems and integration — Physical device control — Data model for computerized numerical controllers — Part 10: General process data. ISO/TC 184/SC 1 Industrial cyber and physical device control, Dec. 2004.
[17] ISO 10303-238:2020 Industrial automation systems and integration — Product data representation and exchange — Part 238: Application protocol: Model based integrated manufacturing. ISO/TC 184/SC 4 Industrial data, Nov. 2020.
[18] ISO 6983-1:1982 Numerical control of machines — Program format and definition of address words — Part 1: Data format for positioning, line motion and contouring control systems. ISO/TC 184/SC 1 Industrial cyber and physical device control, Sept. 1982.
[19] Rodriguez, E., Alvaresa, A., (2019) “A STEP-NC implementation approach for additive manufacturing,” *Procedia Manufacturing, vol. 38*, 2019, pp. 9-16. doi: 10.1016/j.promfg.2020.01.002
[20] ISO 14649-17:2020, Industrial automation systems and integration — Physical device control — Data model for computerized numerical controllers — Part 17: Process data for additive manufacturing. ISO/TC 184/SC 1 Industrial cyber and physical device control, March 2020.
[21] Um, J., Rauch, M., Hascoët, JY., Stroud, I. (2017) “STEP-NC compliant process planning of additive manufacturing: remanufacturing,” *Int. J. Adv. Manuf. Technol. 88*, pp. 1215–1230 (2017). doi:10.1007/s00170-016-8791-1
[22] Um, J., Park, J., Stroud, I.A. (2021) “Squashed-Slice Algorithm Based on STEP-NC for Multi-Material and Multi-Directional Additive Processes,” *Applied Sciences*, 2021; 11(18):8292. doi:10.3390/app11188292
[23] Bonnard, R., Hascoët, JY., Mognol, P., Stroud, I. (2018) “STEP-NC digital thread for additive manufacturing: data model, implementation and validation,” *Int. J. Comput. Integr. Manuf.*, 31:11, 1141-1160, doi: 10.1080/0951192X.2018.1509130
[24] ISO 14649-1:2003 Industrial automation systems and integration — Physical device control — Data model for computerized numerical controllers — Part 1: Overview and fundamental principles. ISO/TC 184/SC 1 Industrial cyber and physical device control, March 2003.
[25] Riaño, C., Rodriguez, E., Alvaresa, A.J. (2019) “A Closed-Loop Inspection Architecture for Additive Manufacturing Based on STEP Standard”, *2019 IFAC Proceedings Volumes*, 52(13):2782-2787. doi: 10.1016/j.ifacol.2019.11.629
[26] Arisoy, Y., Criales, L., Ozel, T., Lane, B., Moylan, S., Donmez, A. (2016) “Influence of Scan Strategy and Process Parameters on Microstructure and Its Optimization in Additively Manufactured Nickel Alloy 625 via Laser Powder Bed Fusion,” Int. J. Mechatronics Manuf. Syst. Available Online: https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=921777
[27] Kumar, S.N. (2014) “Selective Laser Sintering/Melting,” *Comprehensive Materials Processing, vol. 10*, 2014, pp. 93-134. doi:10.1016/B978-0-08-096532-1.01003-7
[28] Milaat, F.A., Yang, Z., Ko, H., Jones, A.T. "Prediction of Melt Pool Geometry Using Deep Neural Networks." Proceedings of the ASME 2021 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 2: 41st Computers and Information in Engineering Conference (CIE). Virtual, Online. August 17–19, 2021. V002T02A037. ASME. doi:10.1115/DETC2021-69259
[29] Zhang, W., Tong, M., Harrison, N.M. (2020) “Scanning strategies effect on temperature, residual stress and deformation by multi-laser beam powder bed fusion manufacturing,” *Additive*

Manufacturing vol. 36, December 2020, 101507. doi: 10.1016/j.addma.2020.101507
[30] Soltani-Tehrani, A., Yasin, M.S., Shao, S., Shamsaei, N. (2021) "Effects of Stripe Width on the Porosity and Mechanical Performance of Additively Manufactured Ti-6Al-4V Parts," *Solid Freeform Fabrication 2021: Proceedings of the 32nd Annual International Solid Freeform Fabrication Symposium*, Austin, TX. doi:10.26153/tsw/17627
[31] Pitassi, D., Savoia, E., Fontanari, V., Molinari, A., Luchin, V., Zappini, G., Benedetti, M. (2017) "Finite Element Thermal Analysis of Metal Parts Additively Manufactured via Selective Laser Melting," In (Ed.), Finite Element Method - Simulation, Numerical Analysis and Solution Techniques. IntechOpen. doi:10.5772/intechopen.71876
[32] Sow, M.C., De Terris, T., Castelnau, O., Hamouche, Z., Coste, F., Fabbro, R., Peyre, P. (2020) "Influence of beam diameter on Laser Powder Bed Fusion (L-PBF) process," *Additive Manufacturing*, *vol. 36*, December 2020, doi: 10.1016/j.addma.2020.101532
[33] Lane, B., Mekhontsev, S., Grantham, S., Vlasea, M., Whiting, J., Yeung, H., Fox, J., Zarobila, C., Neira, J., McGlauflin, M., Hanssen, L., Moylan, S., Donmez, M., and Rice, J., (2016) "Design, developments, and results from the NIST additive manufacturing metrology testbed (AMMT)," *Proceedings of Solid Freeform Fabrication Symposium*, Austin, TX, August 10, 2016, pp. 1145-1160. Available Online: https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=921551
[34] EIA Standard RS-274-D. Interchangeable Variable Block Data Format for Positioning, Contouring, and Contouring/Positioning Numerically Controlled Machines 1979.
[35] Newson Engineering XY2-100 Technical dataset, Available Online: http://www.newson.be/doc.php?id=Xy2-100
[36] STEP Tools, I. Feb 2022; Available Online: https://www.steptools.com/
[37] Bartsch, K., Herzog, D., Bossen, B., Emmelmann, C. (2021) "Material modeling of Ti–6Al–4V alloy processed by laser powder bed fusion for application in macro-scale process simulation," *Materials Science and Engineering: A*, *vol. 814*, May 2021, doi: 10.1016/j.msea.2021.141237